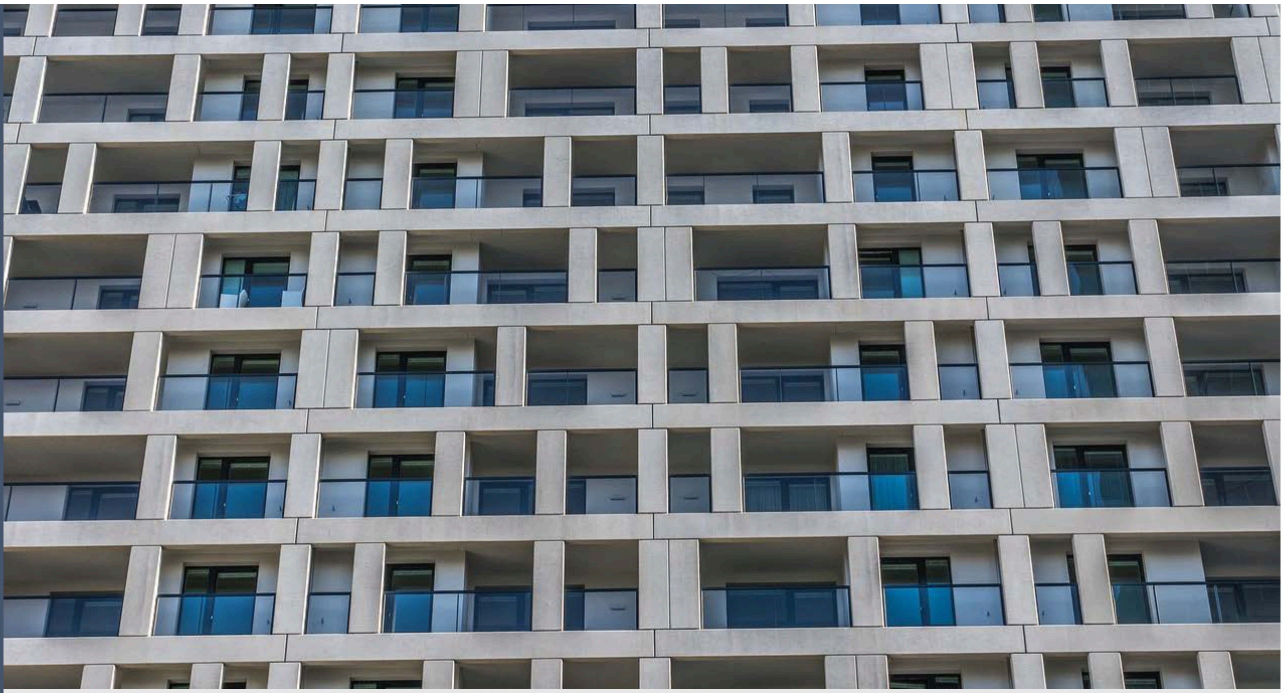

CEMENT'S ROLE IN A CARBON-NEUTRAL FUTURE

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EXECUTIVE SUMMARY

The manufacture of cement, a constituent of concrete, is responsible for 5.6% of global carbon dioxide (CO_2) emissions. 30-40% of these emissions are from thermal fuels (predominantly coal) used to heat the cement kiln, while 60-70% of the emissions are “process emissions” from the breakdown of limestone in a calcination reaction. (A small amount of emissions are also attributable to the generation of electricity used by cement makers.)

After its manufacture, cement naturally sequesters CO_2 from the atmosphere in a process called “carbonation.” Carbonation rates vary considerably with concrete properties, which differ by world region. Globally, roughly a third of cement’s process emissions are re-absorbed within the first two years, and over the course of decades, this share rises to 48%. Cement carbonation is relevant on a global scale but has been omitted from national emissions inventories and global estimates.

Various techniques exist to lower CO_2 emissions from the cement industry, including: energy efficiency technologies, adopting lower-emissions fuels to heat the kiln, substituting other materials for clinker (the constituent of cement responsible for cement’s process emissions), and improving concrete strength or longevity (thereby reducing demand for new concrete). Carbon capture technologies, including post-combustion and oxyfuel technologies, provide options to capture CO_2 emissions that cannot otherwise be avoided. Novel technologies by private firms CarbonCure and Solidia offer additional approaches to reducing emissions from the cement industry.

Modeling of three scenarios finds that capturing 80% of cement’s process emissions (and none of the thermal emissions) by 2050 is sufficient to make cement carbon-neutral, as natural carbonation offsets the remaining emissions. If the thermal fuel supply were to be fully decarbonized by 2050, a process emissions capture rate of 53% achieves carbon-neutral cement. Higher capture rates than these would provide net negative CO_2 emissions and the possibility that simply making concrete could reduce atmospheric CO_2 concentrations.

INTRODUCTION

Cement is a constituent of concrete, a building material that has been in use since ancient Rome. Today, cement is one of the most widely-used materials in the world and is a critical component of roads, bridges, and buildings. Cement production reached 4.3 billion tons/year in 2014[1] and has been growing at a rate of 5-6% annually,[2] driven largely by demand in China and other countries in Asia (Figure 1).[3]

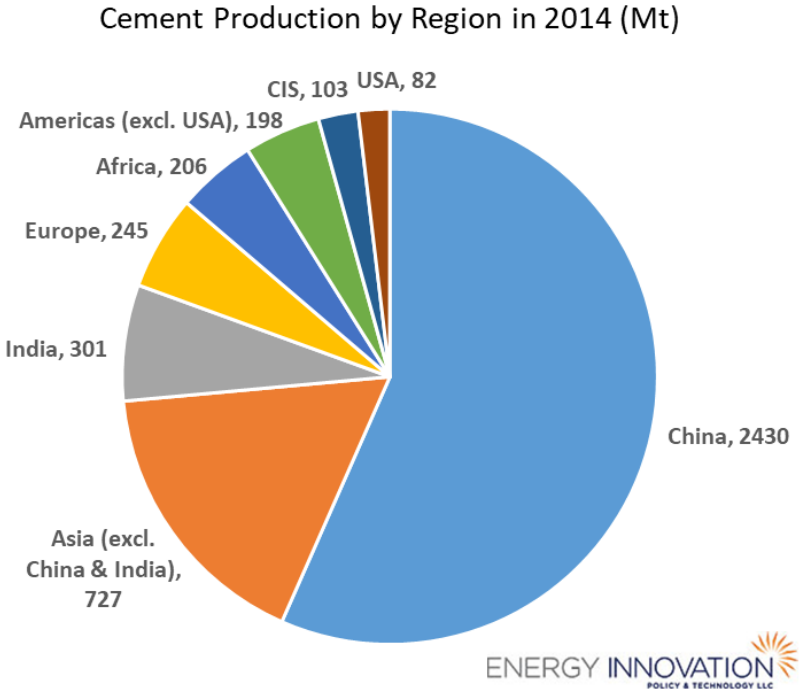

Figure 1: Cement production by region in 2014 (Mt). Data from Sim, Jongsung and Lee, K. H.

The cement industry is a major contributor to climate change. The cement manufacturing process results in a large quantity of carbon dioxide (CO_2) emissions: roughly 5.6% of the global total (as of 2015).[4] In order to protect human society and keep global warming below 2-3°C, it will be necessary to reduce greenhouse gas (GHG) emissions to near-zero by 2050, and likely to remove GHGs from the atmosphere on a net basis in the latter half of the century (see the blue

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[1] Sim, Jongsung and Lee, K. H. 2015. Sustainable Concrete Technology. *Civil Engineering Dimension*, Vol 17, No 3, 158-165. https://www.researchgate.net/publication/294104534_Sustainable_Concrete_Technology

[2] Aether Cement. Reducing the Carbon Footprint of Cement. http://www.aether-cement.eu/reducing-the-carbon-footprint-of-cement.html

[3] Sim, Jongsung and Lee, K. H.

[4] Le Quéré, et al. 2016. Global Carbon Budget 2016. Earth System Science Data. https://doi.org/10.5194/essd-8-605-2016. p 629.

and green emissions trajectories in Figure 2).[5] Therefore, in order for cement to be a sustainable choice of building material for the 21st century and beyond, it is important to reduce its carbon intensity to near-zero levels as soon as is technically feasible.

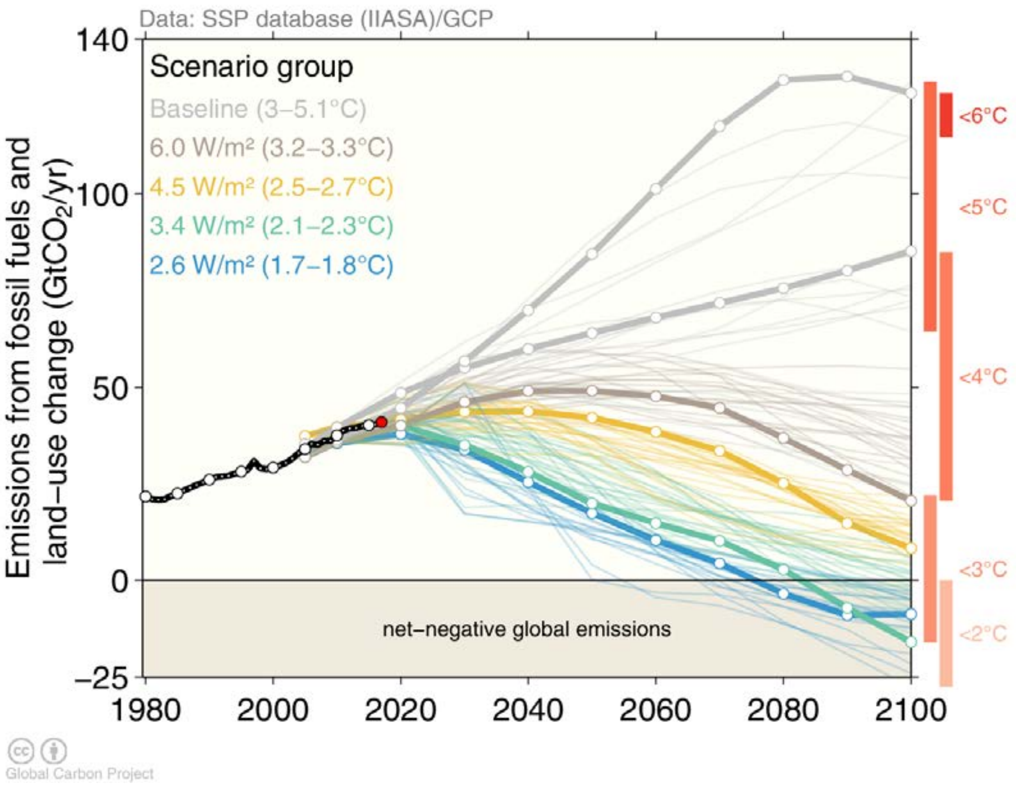

Figure 2: Global emissions trajectories through 2100 and corresponding probable amounts of global warming (the red bars at the right). The green and blue scenarios, which keep warming below 2.5°C, require net-negative global emissions in the second half of the century. Figure from Global Carbon Project.

SOURCES OF CEMENT EMISSIONS

Cement manufacturing releases CO_2 through two types of activities: energy use and calcination reactions.[6] The cement manufacturing process can be broken down into 10 steps, from quarrying the raw materials to grinding and storing the final product (Figure 3).[7]

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[5] Global Carbon Project. 2017. Global Carbon Budget 2017. http://www.globalcarbonproject.org/carbonbudget/index.htm

[6] Transportation of raw materials, intermediate products, or final products may also generate emissions, but transportation emissions are not within the scope of this analysis.

[7] International Energy Agency and Cement Sustainability Initiative. 2018. Technology Roadmap: Low-Carbon Transition in the Cement Industry. p12-14. http://www.iea.org/publications/freepublications/publication/TechnologyRoadmapLowCarbonTransitionintheCementIndustry.pdf

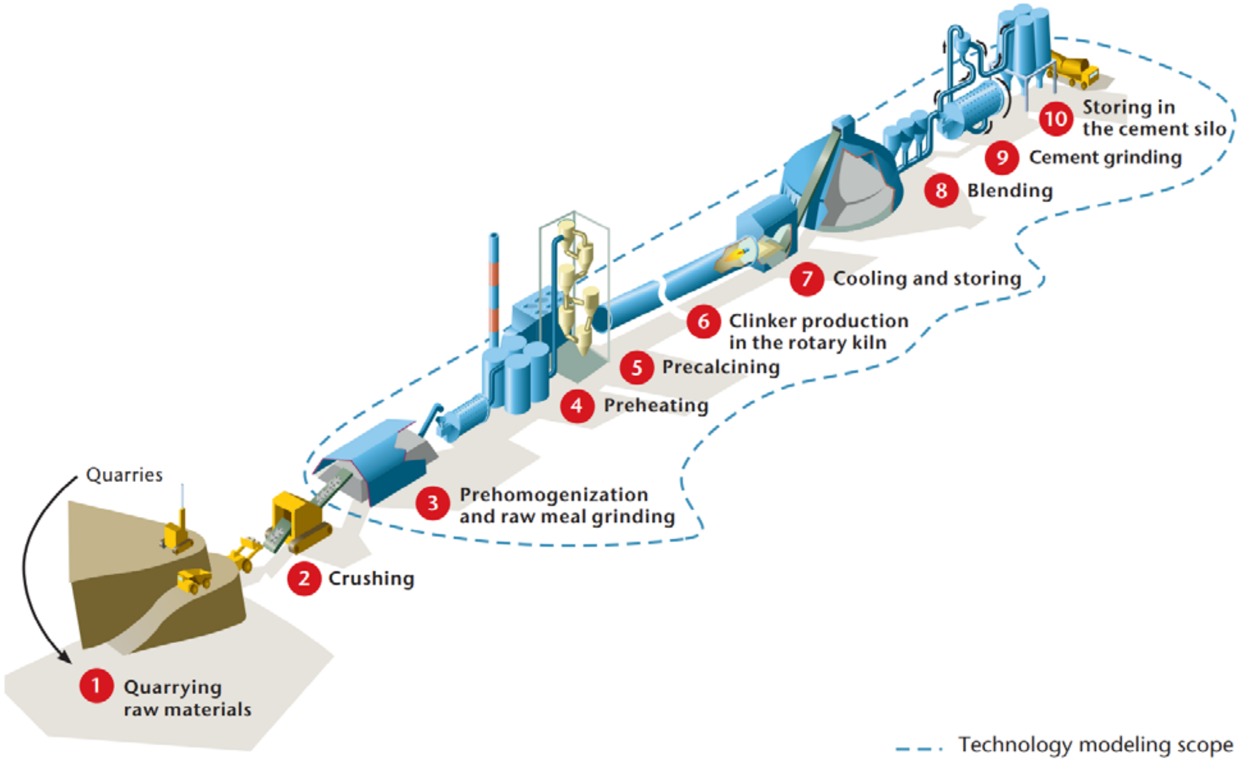

Figure 3: Steps in the cement-making process. "Technology modeling scope" refers to the steps considered in an International Energy Agency analysis of abatement opportunities in the cement industry. Figure from International Energy Agency and Cement Sustainability Initiative (p 12).

Some steps, such as grinding the input materials and the final product, are typically powered by electricity and have no on-site, or "direct," emissions. Thermal fuels (typically coal[8]) are used to heat a precalciner and a rotary kiln, in which input materials reach temperatures over 1400°C.[9] The fossil fuels burned to generate this heat are responsible for roughly 30-40% of the direct CO_2 emissions from cement manufacture.[10]

The remaining 60-70% of the direct CO_2 emissions come from a chemical reaction that takes place in the precalciner, where limestone (largely calcite and aragonite, with chemical formula $CaCO_3$)[11] is broken down into lime (CaO) and carbon dioxide (CO_2). The CO_2 is then released to the atmosphere, while the lime is used to make clinker, the main component of cement. These are called "process emissions," to distinguish them from energy-related emissions.

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[8] IPCC. 2014. AR5 WG3 Chapter 10, Section 10.4.2. https://www.ipcc.ch/pdf/assessment-report/ar5/wg3/ipcc_wg3_ar5_chapter10.pdf

[9] Global CCS Institute (1). 2008. CO2 Capture in the Cement Industry. 2.4: Cement Plant Descriptions. https://hub.globalccsinstitute.com/publications/co2-capture-cement-industry/24-cement-plant-descriptions

[10] International Energy Agency and Cement Sustainability Initiative. p 12.

[11] British Geological Survey. The Composition of Limestone. http://www.bgs.ac.uk/discoveringGeology/geologyOfBritain/limestoneLandscapes/whatIsLimestone/composition.html

CEMENT CARBONATION (REUPTAKE OF CO_2)

The cement within concrete reabsorbs some of the emitted CO_2 during the decades after its manufacture, a process called "carbonation." The fact that concrete reacts with atmospheric carbon dioxide in the years the concrete is in use is well known to the cement industry,[12] but this effect has been viewed negatively due to the risk of corroding the steel reinforcements inside reinforced concrete.[13,14] Consideration of this effect as a potential atmospheric carbon dioxide sink for climate change mitigation is relatively recent.

TESTING CARBONATION RATES AND REGIONAL VARIANCE

Determining the rate at which carbonation proceeds in concrete can be challenging, as many factors influence the carbonation rate, such as the type and quality of the concrete, the humidity of the environment, the exposed surface area, and whether a CO_2-impermeable surface coating has been applied.

Freshly manufactured concrete is highly basic (with a pH of about 13), but carbonated concrete is close to neutral acidity (with a pH of around 8.5).[15] Therefore, measurements of the depth to which CO_2 has penetrated within concrete can be taken using phenolphthalein indicator solution, a chemical that turns purple when exposed to a base. These tests show that in the first year of service, carbonation can penetrate from 1 mm (in dense, dry concrete) up to 5 mm or more (in more permeable concrete with higher water content),[16] with depth increasing in subsequent years. Carbonation proceeds fastest when relative humidity is between 50 and 75 percent, since the reaction requires water to proceed, but too much water can fill up the pores in the concrete and inhibit CO_2 penetration.[17]

Figure 4: Carbonation depth of 10 mm (gray color) after 6 months in outdoor conditions in Shenyang, China. Figure from Xi et al. (supplement, tab "SI data 15")

Tests of concrete in China have revealed carbonation penetration of over 10 mm in depth within the first

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[12] Portland Cement Association. CO_2 and the Concrete Industry: Cement and Concrete as a Carbon Dioxide Sink. http://www.cement.org/for-concrete-books-learning/concrete-technology/concrete-design-production/concrete-as-a-carbon-sink

[13] Ronacrete. Carbonation of Reinforced Concrete. https://www.ronacrete.co.uk/carbonation-reinforced-concrete/

[14] Silva, A. et al. 2014. Statistical modelling of carbonation in reinforced concrete. *Cement and Concrete Composites*. https://www.sciencedirect.com/science/article/pii/S095894651300200X

[15] Grubb, Jennifer et al. 2013. Testing pH of Concrete. Concrete Science. http://www.concretescience.com/wp-content/uploads/2013/02/ph-of-Concrete.pdf.

[16] WHD Microanalsysis Consultants Ltd. Carbonation of concrete. https://www.understanding-cement.com/carbonation.html

[17] Ware, Toby. 2013. Diagnosing and repairing carbonation in concrete structures. *Journal of Building Survey, Appraisal, & Valuation*. Vol 1, No 4, p 341. https://www.henrystewartpublications.com/sites/default/files/Ware.pdf

six months of service (Figure 4).[18] Concrete in China is generally of poorer quality than concrete made in Western countries, contributing to the short lifetimes of concrete buildings in China (typically less than 40 years).[19] It is possible that industry's understanding of carbonation rates, developed in the United States and Europe, may not accurately predict carbonation in the types of concrete commonly used in East Asia (where the majority of the world's concrete is made).

CARBONATION RATE ESTIMATES FROM THE LITERATURE

Various studies have attempted to ascertain the rate at which carbonation proceeds in concrete. Most of these studies have limited geographic scope, and most consider only completed structures during their service lives, neglecting carbonation of kiln dust, waste concrete, and rubble following the demolition of concrete structures. Estimates of carbonation rates vary widely, and experts have not yet reached agreement on a single methodology or global average value. Cement carbonation has not been factored into national emissions inventories and carbon budgets.[20]

A 2005 study of concrete in four Nordic countries estimated that within 50 years, 24.5% to 43% of the concrete used in certain building materials will have carbonated (in hollow core slabs, cast in-situ floors, and façade elements). Penetration depths were generally around 32 mm.[21] A similar study in these countries was conducted in 2007.[22]

A 2017 study of the Itaipu Dam in Paraguay (which opened in 1984) found minimum, average, and maximum carbonation depths of zero, 33, and 72.3 mm.[23] Note that a dam has many surfaces exposed to water, which inhibits carbonation, and so may not be representative of the carbonation to be expected in most concrete structures.

A 2018 study of two 100-year-old bridges in Slovakia sheds light on the effectiveness of CO_2-impermeable coatings on preventing carbonation. Bridge surfaces protected by a 2-3 mm layer of CO_2-impermeable plaster experienced almost no carbonation, while exposed surfaces carbonated to a depth of 60 mm.[24]

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[18] Xi, Fengming et al. 2016. Substantial global carbon uptake by cement carbonation. *Nature Geoscience*. https://www.nature.com/articles/ngeo2840.epdf. See supplementary Excel file, tab "SI data 15".

[19] IPCC.

[20] University of East Anglia. 2016. Cement materials are an overlooked and substantial carbon sink. https://www.uea.ac.uk/about/-/cement-materials-are-an-overlooked-and-substantial-carbon-sink-

[21] Lagerblad, Björn. 2005. Carbon dioxide uptake during concrete life cycle – State of the art. https://www.dti.dk/_/media/21043_769417_Task%201_final%20report_CBI_Bjorn%20Lagerblad.pdf. p 31-32.

[22] Pade, Claus and Guimaraes, Maria. 2007. The CO2 uptake of concrete in a 100 year perspective. *Cement and Concrete Research*. https://doi.org/10.1016/j.cemconres.2007.06.009.

[23] Possan, Edna et al. 2017. CO2 updake potential due to concrete carbonation: A case study. *Case Studies in Construction Materials*. https://doi.org/10.1016/j.cscm.2017.01.007. p 153.

[24] Janotka, Ivan; Bačuvčík, Michal; and Paulík, Peter. 2018. Low carbonation of concrete found on 100-year-old bridges. Case Studies in Construction Materials. https://doi.org/10.1016/j.cscm.2017.12.006. p 110.

A 1997 study of 18 bridges in Florida (aged from 14-56 years at the time of the study) found carbonation depths up to 50 mm, with an average of 10 mm.[25]

A recent, major study of cement carbonation by Fengming Xi et al. provides new understanding of the rate and magnitude of the carbonation process worldwide, accounting for regional variation, and including carbonation of kiln dust, waste concrete, and post-demolition rubble (including the share that is recycled).[26] The specific values vary by type of cement, but on a global average basis, roughly a third of cement's process emissions are re-absorbed within the first two years, and over the course of decades, this share rises to about 48% (Figure 5).[27]

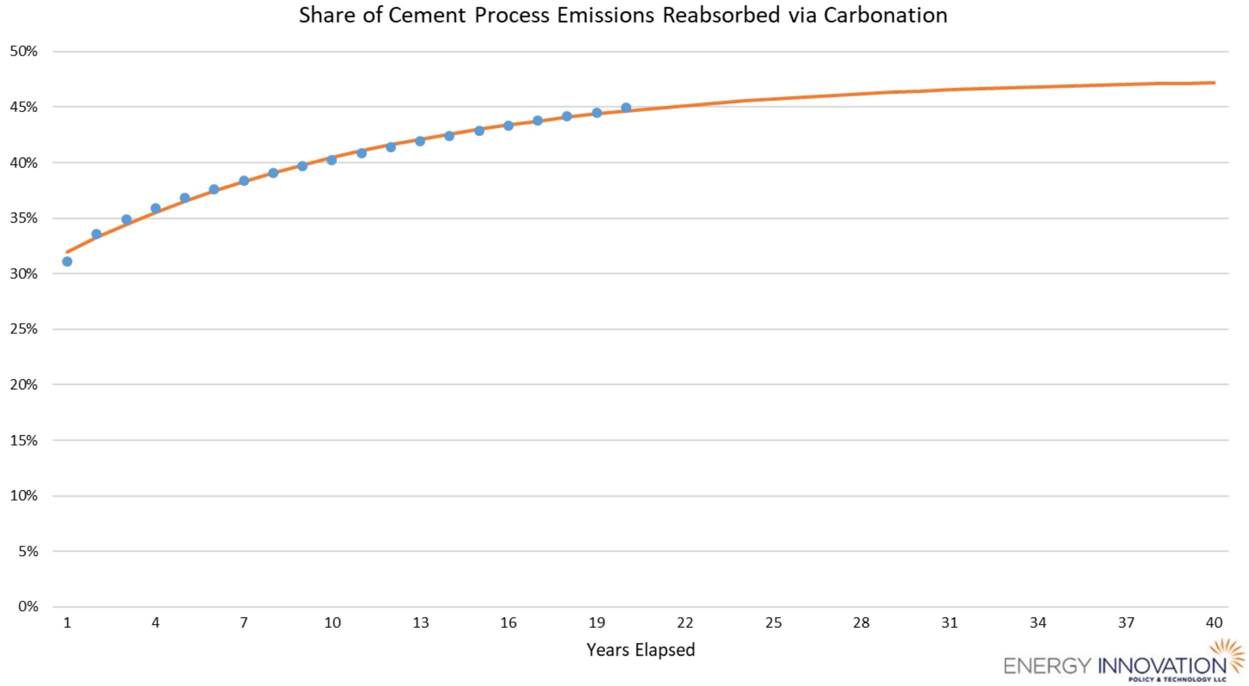

Figure 5: Data points (in blue) and curve fit (in orange) for the share of cement process emissions that are reabsorbed via carbonation in the 40 years following the cement's manufacture. We only use the most recent 20 years of data because cement composition has changed over time (for example, due to regional variations combined with the rise of China as the world's major cement producer), so cement made in the mid-to-late 1900s is less reflective of cement being made today. Data from Xi et al.

Xi et al. found that from 1930 through 2013, 10.4 Gt of carbon (38.1 Gt CO_2) were emitted from cement calcination reactions, while 4.5 Gt of carbon (16.5 Gt CO_2) were taken up by carbonating cement.[28] Worldwide CO_2 uptake in 2013 from carbonating cement was 245 million tons,[29] a quantity of CO_2 slightly larger than the annual CO_2 emissions of Spain.[30]

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[25] Alberto A. Sagüés et al. 1997. Carbonation in Concrete and Effect on Steel Corrosion. https://pdfs.semanticscholar.org/ad7c/bcfada069b92dfd2cd27f41fc034d4f071cb.pdf. p 2.

[26] Xi et al.

[27] Xi et al.

[28] Xi et al.

TECHNIQUES TO REDUCE CO_2 FROM CEMENT

There are a variety of techniques that may reduce the net amount of CO_2 emitted by cement. The techniques discussed below include measures that reduce direct energy-related emissions, process emissions, electricity consumption, or all three. Some of the techniques (e.g. energy efficiency, clinker substitution) are already in use commercially to varying degrees, and they can even be cost-saving, but further progress is needed to refine them and achieve greater emissions reductions. Other techniques (e.g. carbon capture and sequestration) are less-developed and incur added costs, but may be crucial for achieving further abatement once lower-cost, nearer-term options are exhausted.

ENERGY EFFICIENCY

Various technologies can be used to increase the efficiency of heating materials in the precalciner and kiln to form clinker. This reduces thermal energy consumption and associated CO_2 emissions. Today's international best practice energy use is 3.0-3.4 GJ/ton clinker, while the theoretical minimum energy use is 1.85-2.80 GJ/ton clinker (varying with moisture content of the input materials).[31] Some technologies and techniques that help to reduce thermal energy use include:

- Use a dry-process kiln. These kilns utilize input materials with lower moisture content, so less heat need be used to evaporate water.
- Use a kiln with a precalciner and multistage preheater. These equipment allow the input materials to be dried using waste heat before they enter the kiln.
- Add mineralisers to the raw materials to reduce the temperature at which they convert into clinker.
- Operate the kiln with oxygen-enriched air.
- Use a grate clinker cooler, which is better at recovering usable excess heat than a planetary or a rotary cooler.[32]

Electricity in cement manufacturing is primarily used for grinding raw materials, fuel, and cement. Replacing ball mills with high-pressure grinding rolls or vertical roller mills can reduce electricity demand from grinding by 50-70%.[33] If the electricity is generated from fossil fuels, electricity efficiency can reduce upstream emissions.

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[29] Xi et al.

[30] World Bank. Database, indicator "CO2 emissions (kt)." https://data.worldbank.org/indicator/EN.ATM.CO2E.KT?end=2014&start=1960&view=chart.

[31] International Energy Agency and Cement Sustainability Initiative. p 23.

[32] International Energy Agency and Cement Sustainability Initiative. p 24.

[33] International Energy Agency and Cement Sustainability Initiative. p 24.

FUEL SWITCHING AND ELECTRIFICATION

Worldwide, 70% of cement thermal energy demand is met with coal. Oil and natural gas provide 24% of the thermal energy, and biomass and wastes contribute the remainder.[34] The share of kilns using biomass or waste fuels can be increased. These fuels offer a lower CO_2 emissions intensity than coal, although more fuel may be needed per ton of clinker produced, and exhaust treatment technologies are needed to mitigate the high concentrations of particulates that may be emitted.[35] In the longer term, there may exist options for electrification of heat creation, such as induction or microwave heating.[36]

SUBSTITUTE OTHER MATERIALS FOR CLINKER

The calcination reaction that releases CO_2 is a step in the production of clinker, the main component of cement. Other materials, such as fly ash or blast furnace slag,[37] may be blended into the cement, thereby reducing the amount of clinker required per ton of cement produced. The European Cement Association indicates that the minimum achievable percentage of clinker in cement is 70%,[38] while the International Energy Agency estimates 60% clinker content is achievable by 2050.[39] As of 2006, the ratio of clinker-to-cement ranges from 74% to 84%, varying by world region (Table 1). The global average is 78%.[40] If all cement worldwide were made with 60% clinker, this would lower cement process emissions by 23%.

World Region	Clinker to Cement Ratio
North America	84%
Asia excl. China, India, CIS, and Japan	84%
Japan, Australia, and New Zealand	83%
CIS (Russian Commonwealth)	80%
Africa and the Middle East	79%
Europe	76%
China and India	74%
Latin America	74%
World Average	**78%**

Table 1: Cement to Clinker Ratio by World Region in 2006

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[34] International Energy Agency and Cement Sustainability Initiative. p 28.

[35] IPCC.

[36] Brolin, Magnus et al. SP Technical Research Institute of Sweden and Chalmers University of Technology. p44. https://www.diva-portal.org/smash/get/diva2:1073841/FULLTEXT01.pdf

[37] Aether Cement.

[38] European Cement Association (CEMBUREAU). The Role of Cement in the 2050 Low Carbon Economy. http://lowcarboneconomy.cembureau.eu/index.php?page=clinker-substitution

[39] International Energy Agency and Cement Sustainability Initiative. p 41.

[40] World Business Council for Sustainable Development. 2009. Cement Industry Energy and CO_2 Performance: Getting the Numbers Right. p 22. http://www.wbcsdcement.org/pdf/CSI%20GNR%20Report%20final%2018%206%2009.pdf

IMPROVED CONCRETE STRENGTH, LONGEVITY, OR BUIDLING DESIGN

One way to reduce emissions from the cement industry is to reduce the quantity of material demanded. Essentially all cement is used in concrete, so there are two main approaches to reducing cement use: to design buildings and infrastructure to use less concrete, or to design them to last longer before they must be replaced. Using curved fabric molds to shape concrete can reduce concrete use by up to 40% relative to standard geometries with sharp angles and corners.[41] Similarly, using high-strength concrete blends or pre-stressing concrete using tensioned steel cables can reduce the amount of concrete needed to achieve the required structural integrity.[42]

In some applications, it may be possible to substitute other materials for concrete, but potential replacement materials have their own shortcomings. For example, steel can substitute for concrete in some buildings, but the manufacture of steel is itself energy-intensive and generates CO_2 emissions. Other replacement materials may not have the necessary physical properties. For example, relative to concrete, wood has a lower strength-to-volume ratio and is more susceptible to fire.[43]

A promising option is to design and maintain structures to extend their service lives. Today, concrete building lifetimes are less than 80 years in much of the world and less than 40 years in East Asia.[44] Poor building design with little attention to quality and poor maintenance result in short building lifetimes. CO_2-impermeable surface coatings can greatly delay natural carbonation,[45] which can prevent the corrosion of steel reinforcements inside reinforced concrete and prolong the life of these structures (but is unnecessary for non-reinforced concrete).[46] With proper maintenance, concrete structures could last well over 200 years.[47] The Pantheon in Rome, built in 126 CE, is composed of 4,500 tons of concrete. It still stands today.[48]

CAPTURING CO2 FROM WASTE GAS STREAMS

The breakdown of limestone in the precalciner produces a stream of CO_2-rich waste gas, and combustion of fuel to heat the kiln also generates CO_2. A variety of technology options for

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[41] IPCC.

[42] Allwood, Julian and Jonathan Cullen. 2012. Sustainable Materials Without the Hot Air. UIT Cambridge Ltd. p 297.

[43] Allwood, Julian and Jonathan Cullen.

[44] IPCC.

[45] Janotka, Ivan; Bačuvčík, Michal; and Paulík, Peter.

[46] Scrivener, Karen L.; John, Vanderley M.; and Gartner, Ellis M. 2017. Eco-efficient cements: Potential economically viable solutions for a low-CO2 cement-based materials industry. UN Environment Program. http://wedocs.unep.org/bitstream/handle/20.500.11822/25281/eco_efficient_cements.pdf. p 9.

[47] IPCC.

[48] Allwood, Julian and Jonathan Cullen.

capturing these CO_2 emissions exist or are in development. These technologies generally fall into two categories: post-combustion technologies and oxyfuel technologies.[49]

Post-combustion technologies aim to separate CO_2 from other molecules in the exhaust stream and may be used to capture either energy-related or process CO_2. These technologies are farther along in development than oxyfuel technologies, having been pioneered for use in the electricity generation sector, for example, on coal-fired power plants.[50] Post-combustion technologies can be retrofitted onto existing cement manufacturing equipment, facilitating demonstration projects and deployment. The most advanced post-combustion technology relies on chemical absorption of the CO_2 (typically using amines). Chemical absorption is energy-intensive, requiring heat to regenerate the sorbent and electricity to operate the machinery.[51] Other post-combustion options include the use of membranes or calcium looping. Amine-based absorption has been demonstrated at commercial scale in a pilot project, while the other technologies have only been demonstrated at small or laboratory scales.[52]

Oxyfuel technologies work by reacting fuel with pure oxygen instead of air in the precalciner and sometimes in the kiln.[53] These technologies can generate nearly-pure streams of CO_2 (and water vapor, which is easily removed via a condenser), thus greatly reducing the need for post-combustion separation.[54] The design of oxyfuel systems may also enable the capture of process CO_2 emissions.[55] Oxyfuel technologies have two main downsides. First, they are not compatible with existing cement production equipment: new machinery must be designed that is air-tight, introduces pure oxygen into the precalciner and sometimes the kiln, and captures the resulting gas streams. Second, the creation of pure oxygen requires electricity, which adds cost[56] and may have associated CO_2 emissions if not produced via renewables. The first demonstration project of an oxyfuel carbon capture system is being planned in Europe.[57]

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[49] Global CCS Institute (2). Capture of CO in the cement sector. https://hub.globalccsinstitute.com/publications/technology-roadmap-carbon-capture-and-storage-industrial-applications/capture-co2-0

[50] Global CCS Institute (2).

[51] International Energy Agency and Cement Sustainability Initiative. p 37.

[52] International Energy Agency and Cement Sustainability Initiative. p 37.

[53] Global CCS Institute (2).

[54] Praxair. 2013. CO2 Processing Unit for Oxy-Fuel Fired Rotary Cement Kiln. p 3 and 7. https://ieaghg.org/docs/General_Docs/OCC3/Secured%20presentations/ss_2_Praxair%20OCC3%20CPU%20for%20ECRA%20Study%20Praxair.pdf.

[55] Eriksson, Matias; Hökfors, Bodil; and Backman, Rainer. 2014. Oxyfuel combustion in rotary kiln lime production. *Energy Science & Engineering*. https://onlinelibrary.wiley.com/doi/full/10.1002/ese3.40.

[56] Global CCS Institute (2).

[57] International Energy Agency and Cement Sustainability Initiative. p 38.

NOVEL TECHNOLOGIES

In recent years, certain companies have developed proprietary products or processes that promise to reduce the carbon intensity of cement or concrete manufacture.

CARBONCURE: INJECTION OF CO_2 INTO CONCRETE MIX

CarbonCure™ is a private firm that has developed a technology that injects CO_2 into ready mix concrete during the mixing process (and can also be used during manufacture of concrete blocks).[58] CarbonCure's technology has been adopted by 62 concrete manufacturers, who have collectively produced 1.16 million tons of concrete using the CarbonCure process (through Aug 2018). This has resulted in more than 15,000 tons of avoided CO_2 emissions (relative to the production of a similar amount of ordinary concrete).[59]

In a published study, CarbonCure found that their process reduces net CO_2 emissions from concrete manufacture (relative to ordinary concrete) by 18 kg / cubic meter.[60] The most important driver of this abatement is a reduction in the required percentage of cement in mixed concrete.

Concrete is a blend of cement and other materials, such as gravel, sand, fly ash, or blast furnace slag. The percentage of cement can vary greatly, from as low as 30% to as high as 100%.[61] Different concrete mixes are chosen to impart different properties to the final concrete, such as compressive strength or erosion resistance. Injecting CO_2 during the mixing process increases the strength of concrete, allowing for less cement to be used in the concrete mix. Typically, cement use is reduced by 5%.[62,63] This reduction in cement use reduces the carbon intensity of concrete by 17.6 kg / cubic meter, accounting for 97.7% of the total abatement from CarbonCure's process.[64]

The amount of CO_2 injected is extremely small- roughly 0.6 kg of CO_2 are injected per cubic meter of concrete.[65] Only about 60% of this is mineralized within the concrete, while the rest escapes to the atmosphere.[66,67] This mineralized CO_2 accounts for 1.6% of the total abatement from CarbonCure's process.

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[58] CarbonCure is a registered trademark of CarbonCure Technologies, Inc.

[59] Monkman, Sean (CarbonCure's Vice President of Technology Development). 2018. Email with attachments. 9/22/2018.

[60] Monkman, Sean and MacDonald, Mark. 2017. On carbon dioxide utilization as a means to improve the sustainability of ready-mixed concrete. *Journal of Cleaner Production*. https://doi.org/10.1016/j.jclepro.2017.08.194. Page 373, Table 6.

[61] Gamble, Christie (CarbonCure's Director of Sustainability). Telephone interview. 8/16/2018.

[62] Gamble, Christie.

[63] Monkman, Sean and MacDonald, Mark. P 371.

[64] Monkman, Sean and MacDonald, Mark. P 373, Table 6.

[65] Gamble, Christie.

[66] Monkman, Sean and MacDonald, Mark. P 372.

The remaining 0.7% of the abatement is due to a net reduction in emissions from transportation of raw materials and the substitution of CO_2 for more carbon-intense plasticizing additives.[68]

The effect of CarbonCure on long-term natural carbonation has not been physically tested, but due to the small amount of CO_2 that is injected, CarbonCure believes their process should have minimal impact on subsequent CO_2 sequestration – that is, they believe that injected CO_2 should be additive to natural carbonation.[69]

SOLIDIA: LOW-LIME, LOW-TEMPERATURE CEMENT AND CO_2-CURED CONCRETE

Solidia Technologies is a private company that has developed two products that reduce net CO_2 emissions relative to traditional construction materials: Solidia Cement™ and Solidia Concrete™.[70] Currently, Solidia focuses on manufactured concrete products, such as concrete blocks and paving stones, rather than ready-mix concrete that is poured on-site to form building foundations, walls, pillars, etc.[71] This is because Solidia Cement cures in a pure CO_2 atmosphere, and it is easier to provide a controlled curing environment in a factory than at an outdoor construction site.[72] A ready-mix product suitable for use in poured concrete is under development.[73]

Solidia Cement

In cement manufacture, process emissions come from the breakdown of limestone into lime (CaO) and CO_2. Solidia Cement is a non-hydraulic cement[74] composed of minerals containing less lime than the minerals that compose traditional cement. Specifically, Solidia Cement is composed primarily of wollastonite ($CaO{\cdot}SiO_2$) and rankinite ($3CaO{\cdot}2SiO_2$), while ordinary cement is composed of alite ($3CaO{\cdot}SiO_2$) and belite ($2CaO{\cdot}SiO_2$).[75] Since less lime is required per

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[67] Testing subsequent to publication of CarbonCure's study found the mineralization fraction is likely 70%-80% rather than 60%, but this makes little difference to the total abatement per unit concrete, as mineralization of injected CO_2 accounts for such a small share of total abatement. Ref: Monkman, Sean. Email. 9/26/2018.

[68] Monkman, Sean and MacDonald, Mark. P 371-2.

[69] Gamble, Christie.

[70] Solidia Cement and Solidia Concrete are registered trademarks of Solidia Technologies.

[71] Jain, Jitendra et al. 2014. Solidia Concrete. Solidia Technologies. http://solidiatech.com/wp-content/uploads/2014/02/Solidia-Concrete-White-Paper-FINAL-2-19-14.pdf

[72] DeCristofaro, Nick (Solidia's Chief Technology Officer). Telephone Interview. 8/22/18.

[73] DeCristofaro, Nick.

[74] Hydraulic cements are able to set and cure underwater, while non-hydraulic cements require drier conditions. Hydraulic cements are often used to seal structures against water intrusion (such as foundations) or in applications exposed to water (such as swimming pools and fountains).

[75] Solidia Technologies (1). 2017. The Science Behind Solidia Cement and Solidia Concrete. http://solidiatech.com/wp-content/uploads/2017/01/Solidia-Technologies-Science-Backgrounder-Jan-2017-FINAL.pdf

unit of cement, less limestone needs to be calcinated (broken down). This reduces process emissions by 30%.[76]

Additionally, the clinker in Solidia Cement is produced in a kiln that reaches a maximum temperature of 1250°C, compared to 1450°C for ordinary cement. The lower temperature allows less thermal fuel to be used, reducing emissions. The reduction in thermal fuel use is up to 30%.[77,78]

Ordinary cement emits roughly 500 kg CO_2/ton of process emissions and 300 kg CO_2/ton from the combustion of thermal fuel, for a total of 800 kg CO_2/ton. In contrast, Solidia Cement emits a total of 550 kg CO_2/ton (summing process and thermal emissions).[79]

These figures do not include upstream CO_2 emissions from the generation of electricity used in the manufacturing process. Solidia is of a similar hardness to ordinary cement and is made using the same equipment, so there is no meaningful difference in electricity consumption between the manufacture of Solidia Cement and ordinary cement.[80] The contribution of electricity-related emissions to total cement emissions is small.

Solidia Concrete

Ordinary concrete cures by reacting with water over the course of several weeks. In contrast, Solidia Concrete reacts with the CO_2 molecules within a water-CO_2 solution and cures in 24 hours. During the curing process, the concrete can sequester up to 300 kg of CO_2 per ton of cement used in the concrete.[81] However, it is typical for Solidia to stop the reaction once 240 kg CO_2/ton cement have been sequestered, because the CO_2 must be purchased on the market, and adding more CO_2 than 240 kg is not necessary to meet the strength and durability requirements for the final material. Thus, sequestering the full 300 kg CO_2/ton does not make financial sense today, though it might if a sufficient carbon price were in effect.[82]

In comparison, carbonation of ordinary concrete over 40+ years stores up to 48% of the process emissions from the cement used in the concrete. As noted above, there are roughly 500 kg of CO_2 process emissions per ton of ordinary cement, so natural sequestration will eventually sequester 240 kg of CO_2 per ton of cement used in the concrete, the same amount that Solidia sequesters today during the curing process, and 20% less than Solidia's potential.

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[76] DeCristofaro, Nick et al. 2017. Environmental Impact of Carbonated Calcium Silicate Cement-Based Concrete. *1st International Conference on Construction Materials for Sustainable Future.* https://www.solidlife.eu/sites/solidlife/files/atoms/files/coms2017_fullpaper_solidia.pdf. p 4.

[77] DeCristofaro, Nick et al. p 3-4.

[78] The fact that the percentage reduction in thermal fuel use and the percentage reduction in process emissions are nearly the same is coincidental.

[79] Solidia Technologies (2). Solidia Cement. http://solidiatech.com/applications/adoptions/cement/

[80] DeCristofaro, Nick.

[81] Jain, Jitendra et al.

[82] DeCristofaro, Nick.

Solidia has not physically tested the rate of carbonation of Solidia Cement during the years it is in service. Solidia believes little additional uptake of CO_2 is likely.[83]

TECHNOLOGY COMPARISON

Figure 6 summarizes many of the data from this section of the report. Though it would be ideal to compare emissions from a specific quantity of concrete (rather than cement), the fraction of cement in concrete varies widely, and the thermal and process emissions derive from the cement portion of the concrete. As a result, we work in units of cement, but we adjust the emissions for CarbonCure to reflect the 5% reduction in cement use afforded by CarbonCure's process.

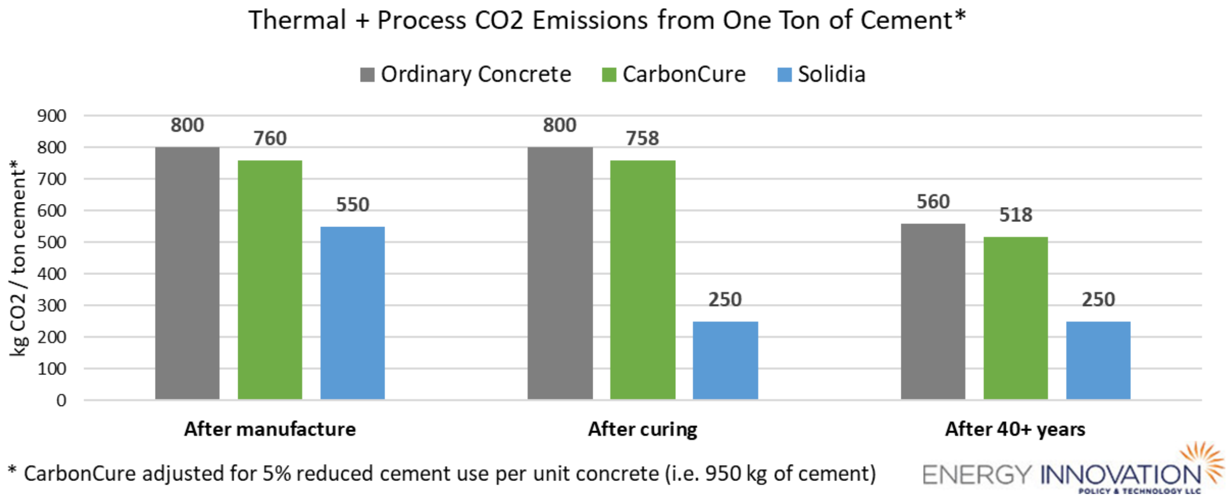

Figure 6: Comparison of net thermal + process (i.e. non-electricity) CO_2 *emissions from three cement technologies at different stages of cement/concrete lifecycle. Assumes CarbonCure does not reduce natural sequestration following curing. Uses Solidia's full potential sequestration during curing (300 kg/ton) rather than today's economically-preferred value (240 kg/ton) and assumes Solidia Cement does not sequester significant additional* CO_2 *during service. Data from Xi et al., CarbonCure, and Solidia.*

PROJECTIONS TO 2050

The International Energy Agency and the Global Cement Sustainability Initiative have estimated the amount of cement that will be produced worldwide through 2050.[84] They provide detailed results of two emissions scenarios: a reference technology scenario (RTS) that assumes only modest improvements in CO_2 emissions intensity of cement production, and a two-degree scenario (2DS) that assumes larger improvements, in line with cement's contribution to global GHG abatement required to limit likely warming to 2°C by 2050. The 2DS features greater progress in energy efficiency and greater deployment of carbon capture and sequestration (CCS) technologies than the RTS.

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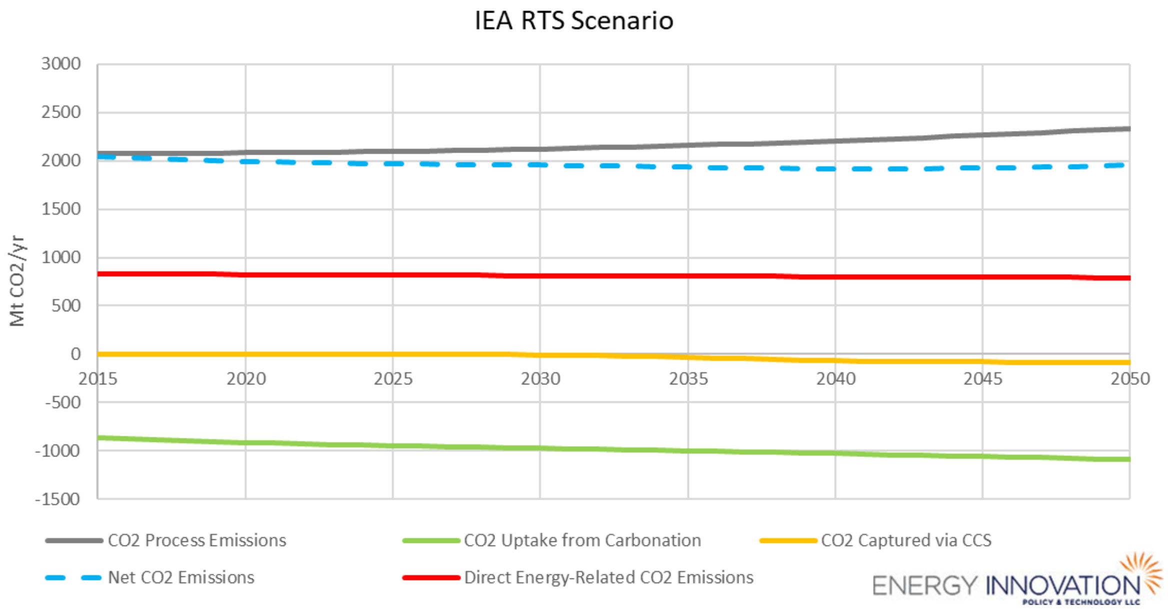
[83] DeCristofaro, Nick.

[84] International Energy Agency and Cement Sustainability Initiative. p 18.

We enhance the IEA's scenarios in two ways. First, we factor in CO_2 sequestration from carbonation of cement through 2050, an effect omitted from IEA's analysis. Second we replace the IEA's process emissions intensities (which range from 0.34 to 0.24 tons of process CO_2 per ton of cement)[85] with a value from Xi et al. (0.5 tons of process CO_2 per ton of cement),[86] a change that helps improve the alignment of IEA's projections with the historical record. Additionally, we add our own scenario, exploring the amount of CCS required to make cement carbon-neutral by 2050. This is the "Carbon Neutral in 2050 Scenario" (CNS). CO_2 emissions, capture, and uptake from carbonation in these scenarios are shown in Figure 7.

All scenarios feature the same process emissions before capture (in gray) and uptake from carbonating cement (in green). Direct energy-related emissions (in red) are slightly lower in the 2DS than in the RTS, and we adopt the IEA's 2DS direct energy-related emissions for the CNS. Emissions associated with the generation of purchased electricity are not included. The only important difference between the three scenarios is the amount of carbon captured and sequestered (in yellow), which is lowest in the RTS (83 Mt CO_2 in 2050), intermediate in the 2DS (552 Mt CO_2 in 2050), and highest in the CNS (1864 Mt CO_2 in 2050). If purchased electricity is emissions-free by 2050, to make cement carbon-neutral in 2050, it is only necessary to capture 80% of the process emissions (and none of the direct energy-related emissions), as the remainder is offset by carbonating cement. This situation is illustrated in the CNS scenario. If the thermal fuel supply were to be fully decarbonized by 2050, capturing just 53% of the process emissions would be sufficient to achieve carbon-neutral cement production.


IEA RTS Scenario

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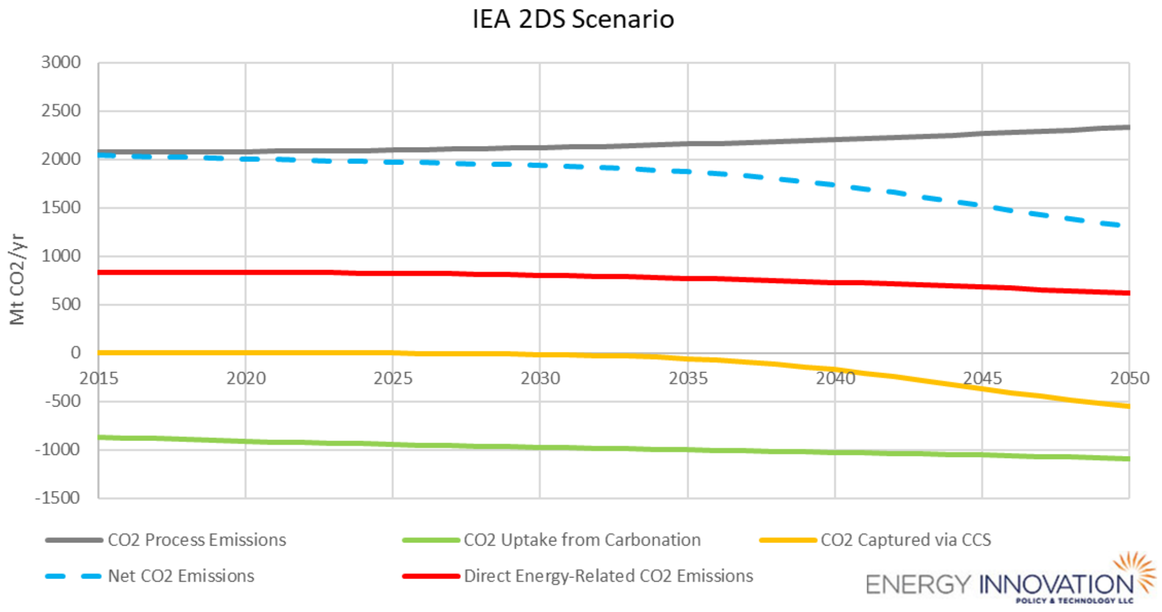
[85] International Energy Agency and Cement Sustainability Initiative. p 18.

[86] Xi et al. Average of most recent 20 years of data.



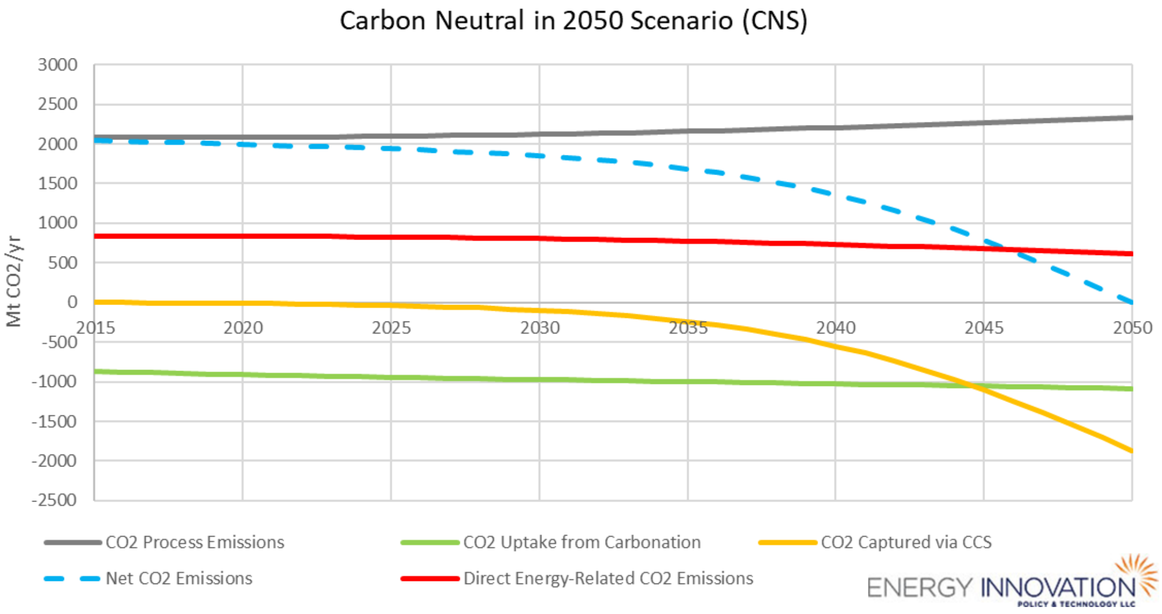


Figure 7: CO2 emissions, capture, and uptake from carbonation in three scenarios.

CONCLUSION

Concrete is the most widely-used, man-made material in the world,[87] and it will be a major constituent of the new buildings and infrastructure that will meet the world's housing, business, and transportation needs in the 21st century. Therefore, it is crucial to ensure that the

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[87] Royal Society of Chemistry. 2008. The Concrete Conundrum. *Chemistry World*. http://www.rsc.org/images/Construction_tcm18-114530.pdf

manufacture of cement, the most emissions-intense component of concrete, can be done in a way that helps to reduce GHG emissions, ultimately to zero.

Fortunately, there are many opportunities to reduce GHG emissions from cement and concrete. Technologies to improve energy efficiency can reduce thermal fuel and electricity-related emissions, while techniques that reduce the need for clinker (such as clinker substitution, increased building longevity, or designs that use less concrete) are effective at reducing both energy-related and process emissions. Novel technologies from firms such as CarbonCure and Solidia provide additional mitigation opportunities.

Cement sequesters CO_2 from the atmosphere for decades, ultimately offsetting about 48% of the process (non-energy) CO_2 emissions from its manufacture. Combined with carbon capture and sequestration (CCS), this trait offers the possibility of using cement as a net carbon sink. Assuming electricity in 2050 is supplied by zero-emissions sources (such as renewables or nuclear), a CCS capture rate of 80% is sufficient to offset all thermal and net process emissions. If the supply of heat can be electrified, a process emissions capture rate of just 53% offers carbon-neutral cement. Higher capture rates than these would provide net negative CO_2 emissions and the possibility that simply making concrete could reduce atmospheric CO_2 concentrations.